Image Credit: DESY, Science Communication Lab

1D MHD, Lagrange Particle, and Radiative Transfer Hybrid Simulations of Relativistic Shock Emissions

Comparison to Thin-shell Approximation

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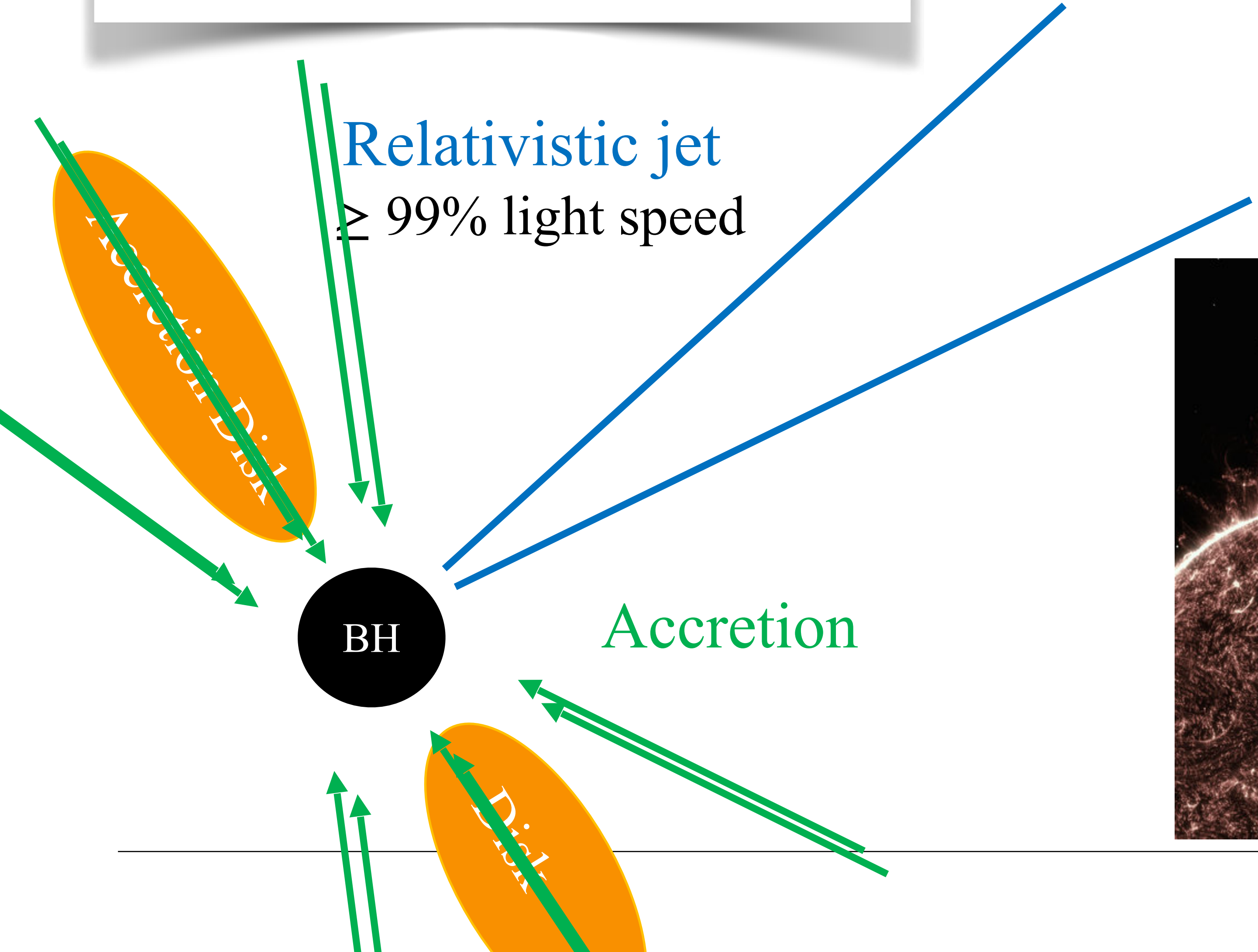
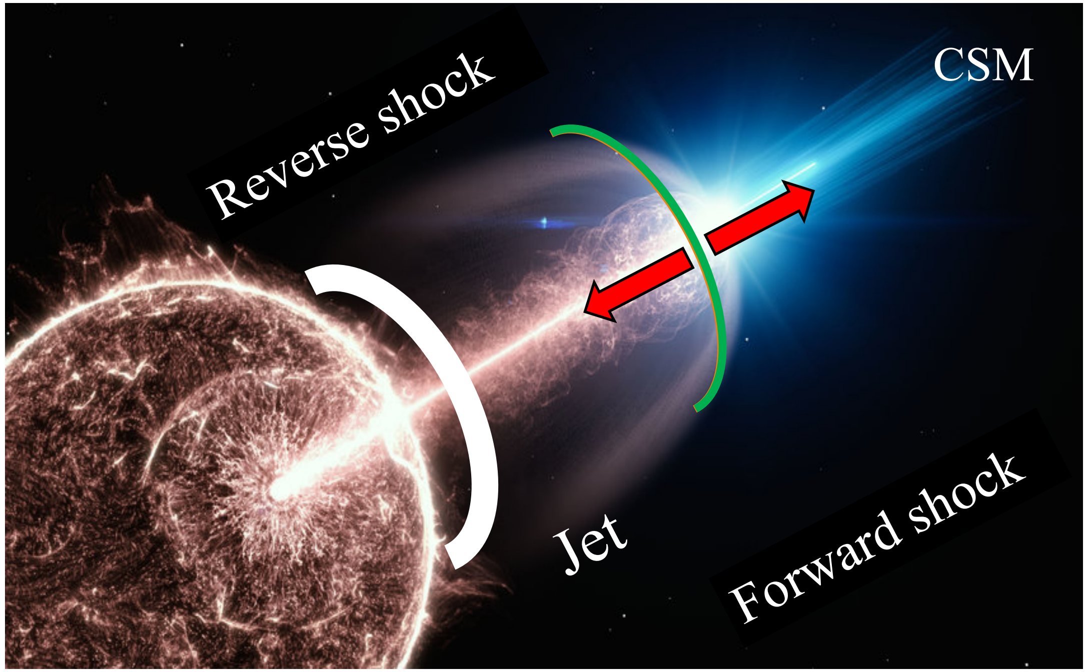
Colaborator: Katsuaki Asano (ICRR)

Gamma-Ray Bursts



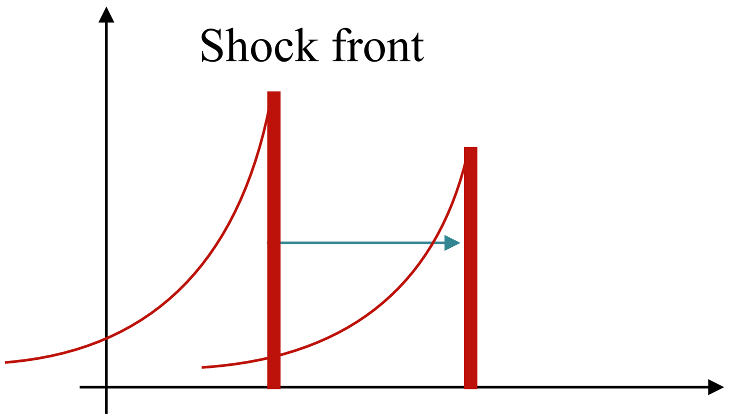
Interaction with Jet and CircumStellar Medium

GRB afterglow

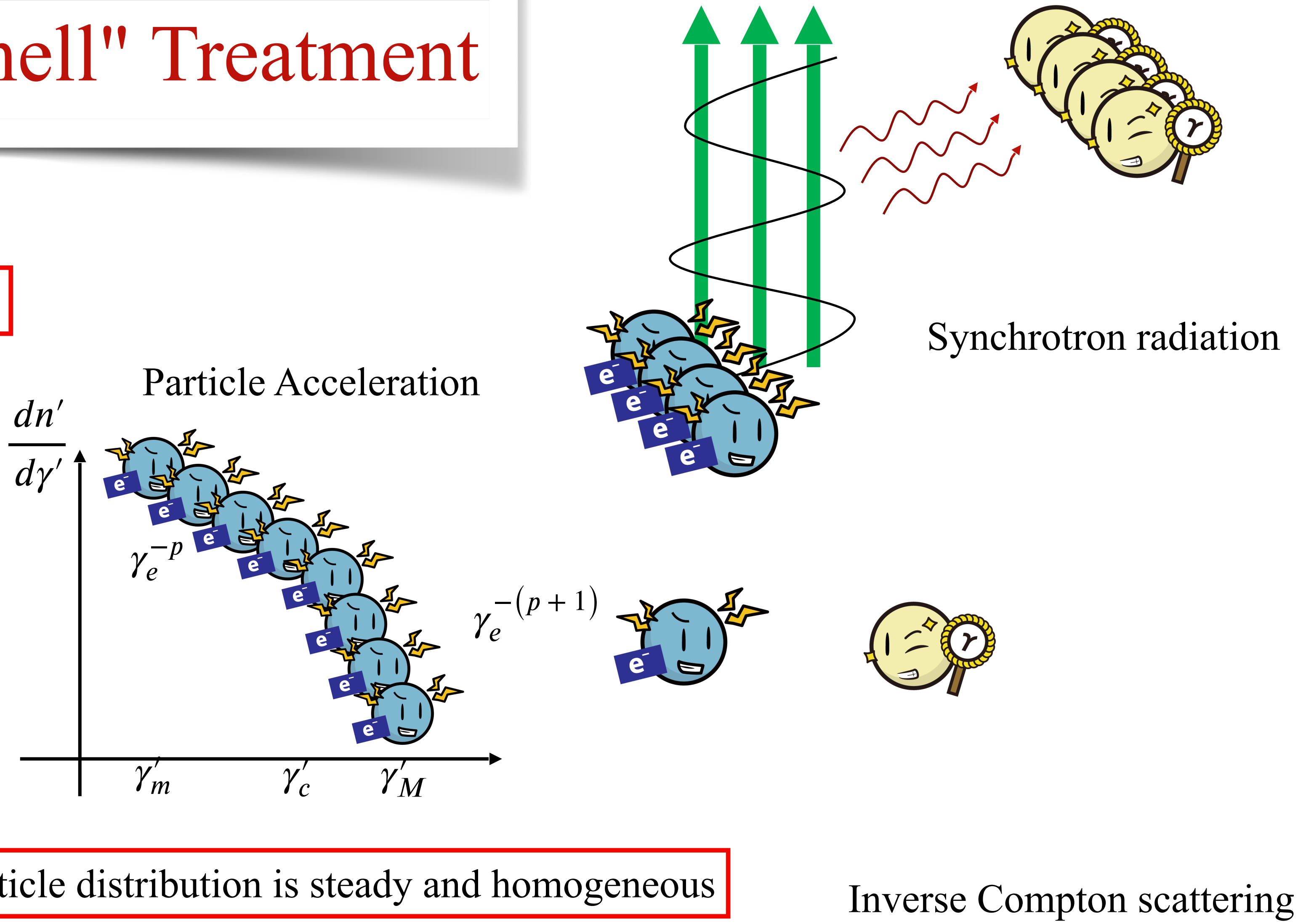


Afterglow as "Thin Shell" Treatment

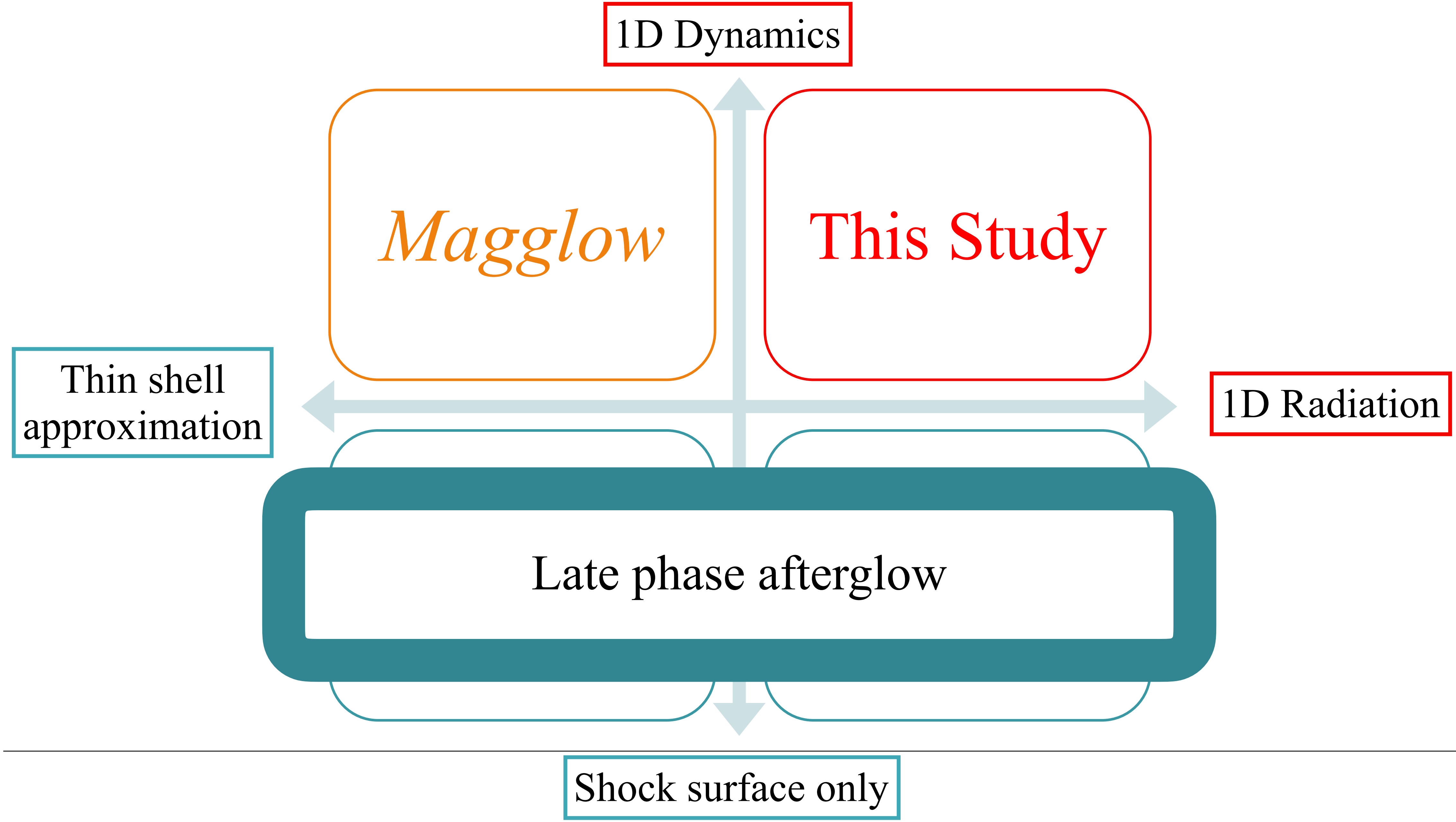
Emissivity is concentrated at the shock surface



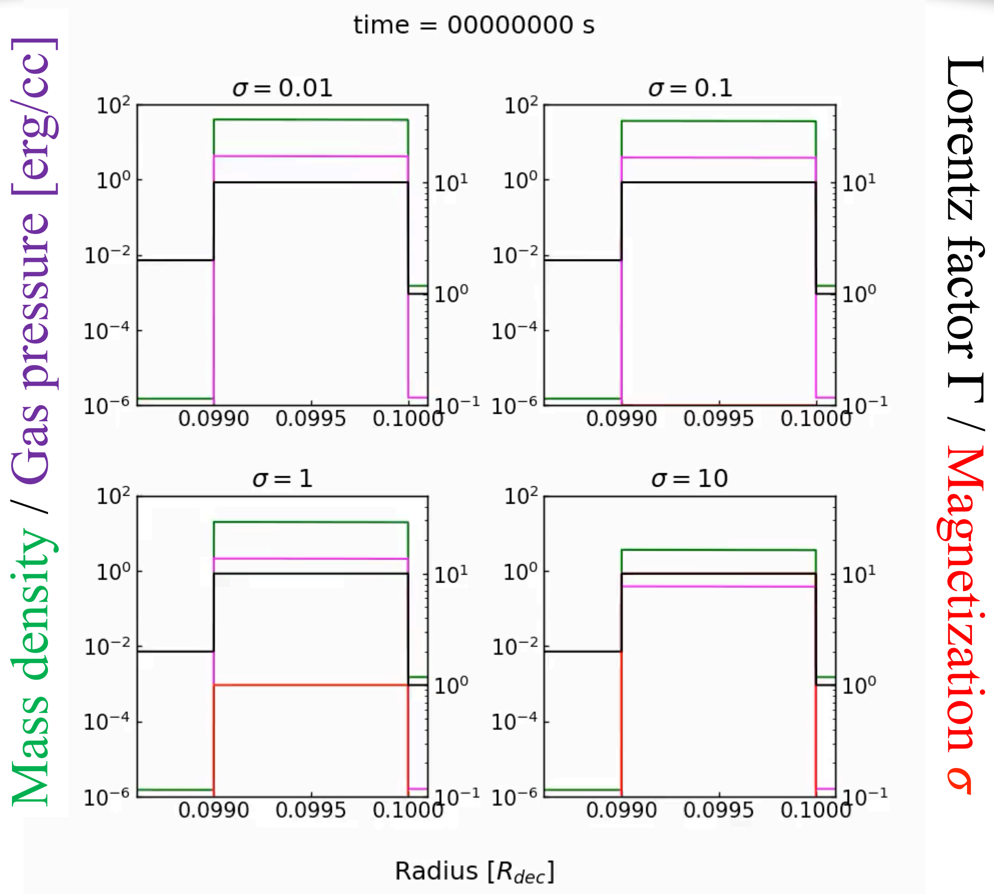
Emission region size $\sim \dfrac{R}{12\Gamma^2}$



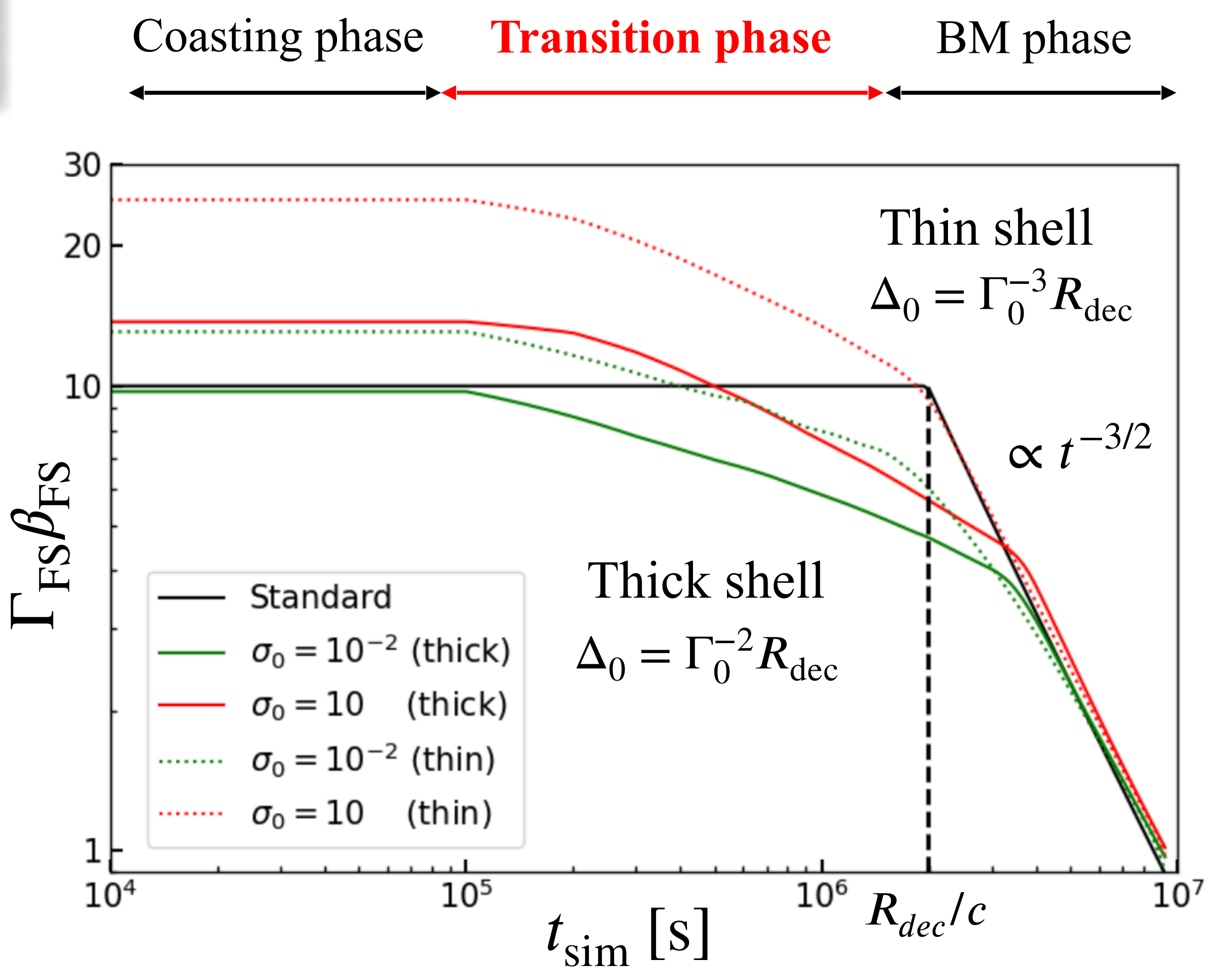
Particle distribution is steady and homogeneous


1D Dynamics
Magglow
This Study
Thin shell
approximation
1D Radiation
Late phase afterglow
Shock surface only

Shock Wave Simulation



σ, Δ affect FS dynamics

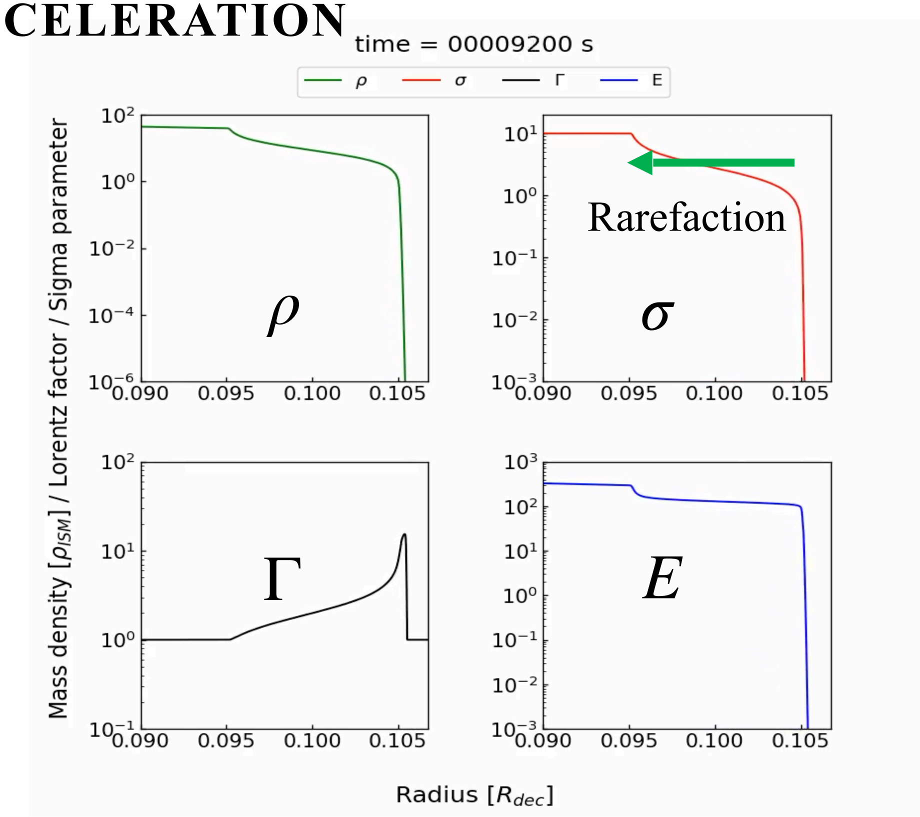


Kusafuka & Asano (2025a)

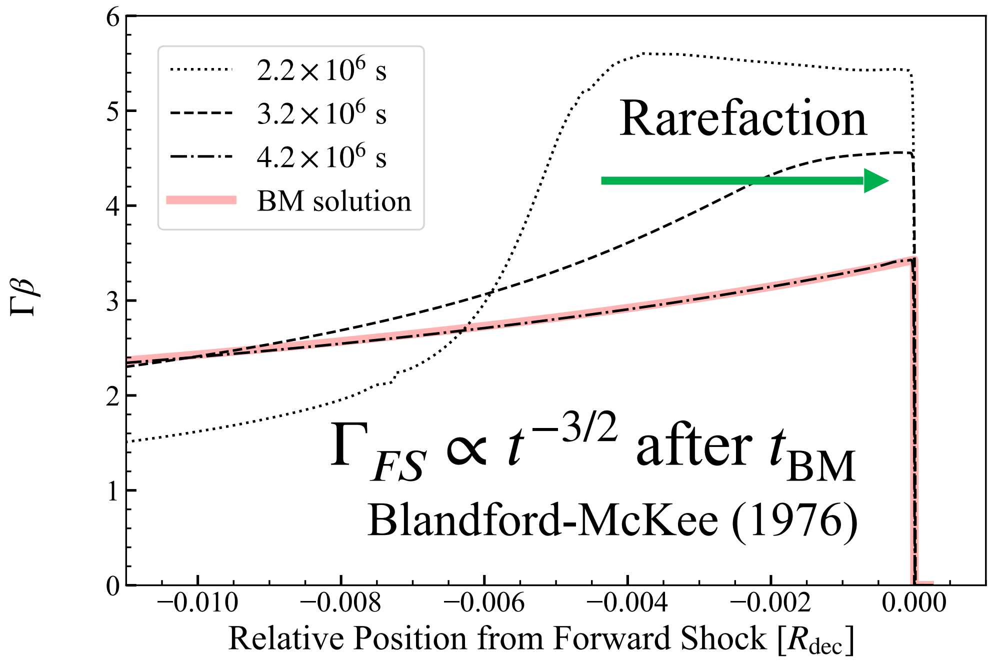
Dynamical Effects

Rarefaction waves regulate the overall dynamics

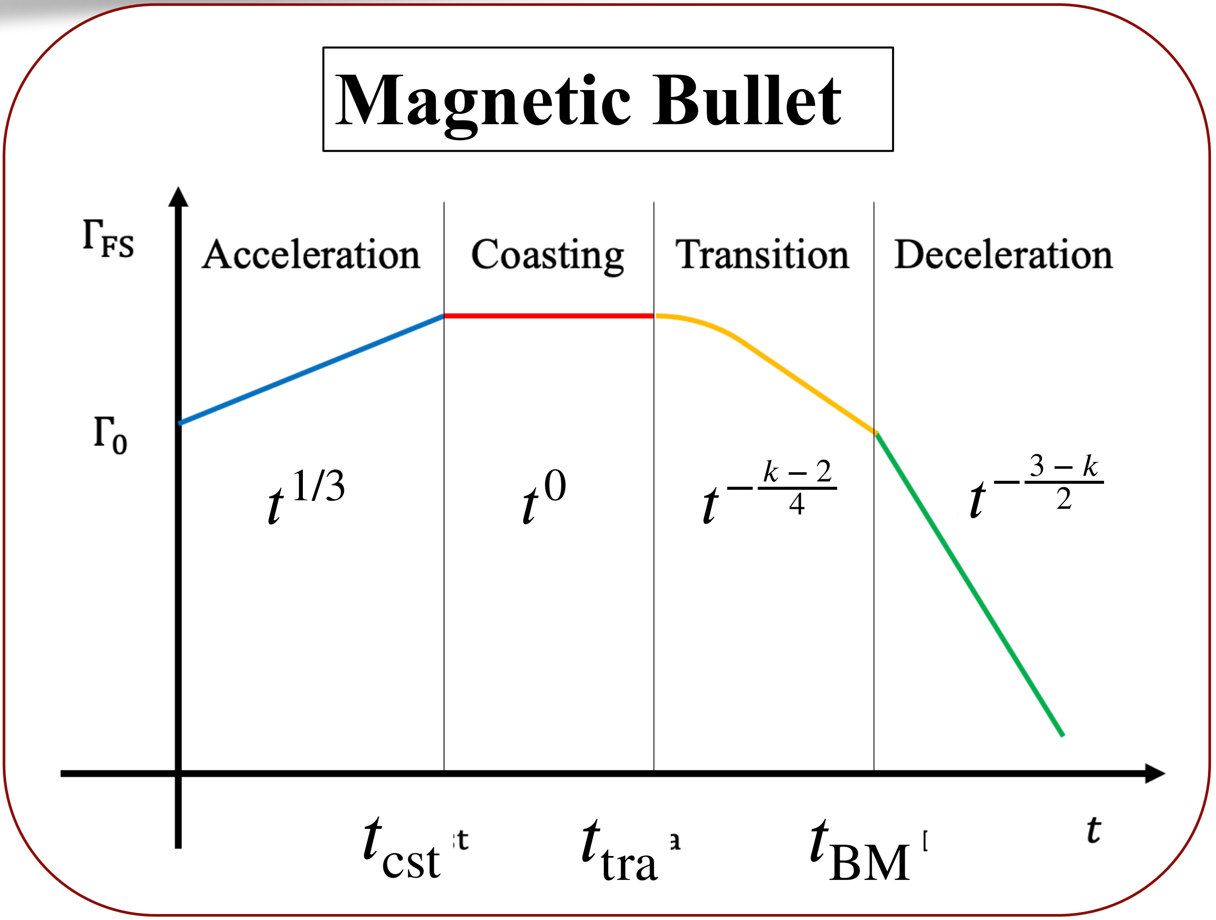
ACCELERATION



DECELERATION

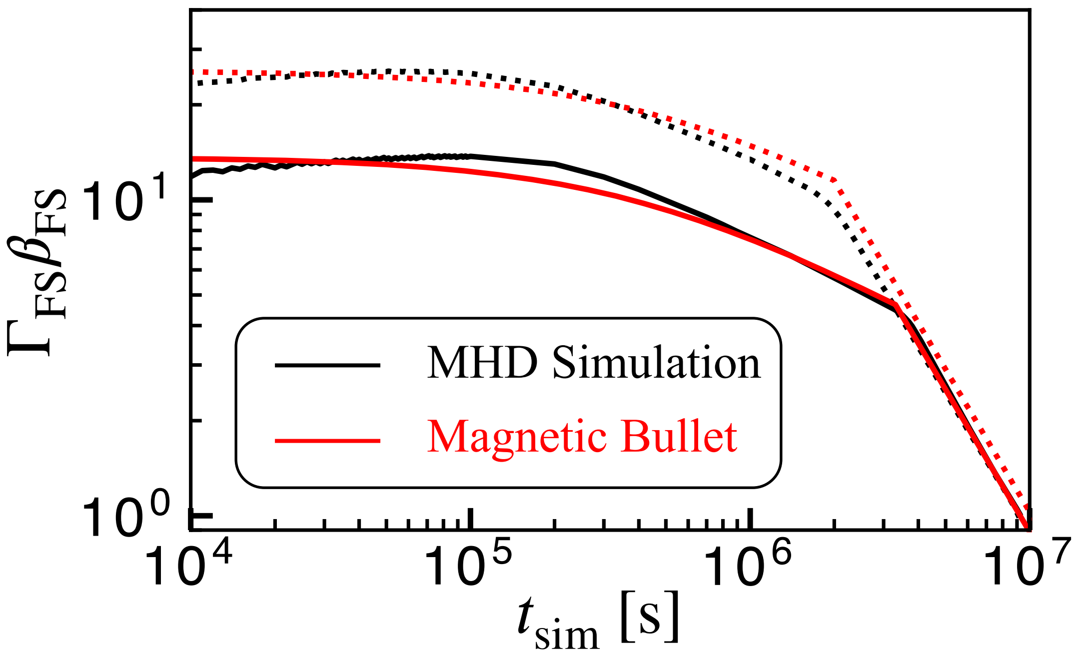


Semi-Analytic Model of Magnetic Bullet Afterglow



Well consistent with simulation results

$E_0 = 10^{50},\ \Gamma_0 = 10,\ \sigma_0 = 10,\ \Delta_0 = R_{dec}/\Gamma_0^{2\sim3}$



Magglow - Multi-Messenger Moderator

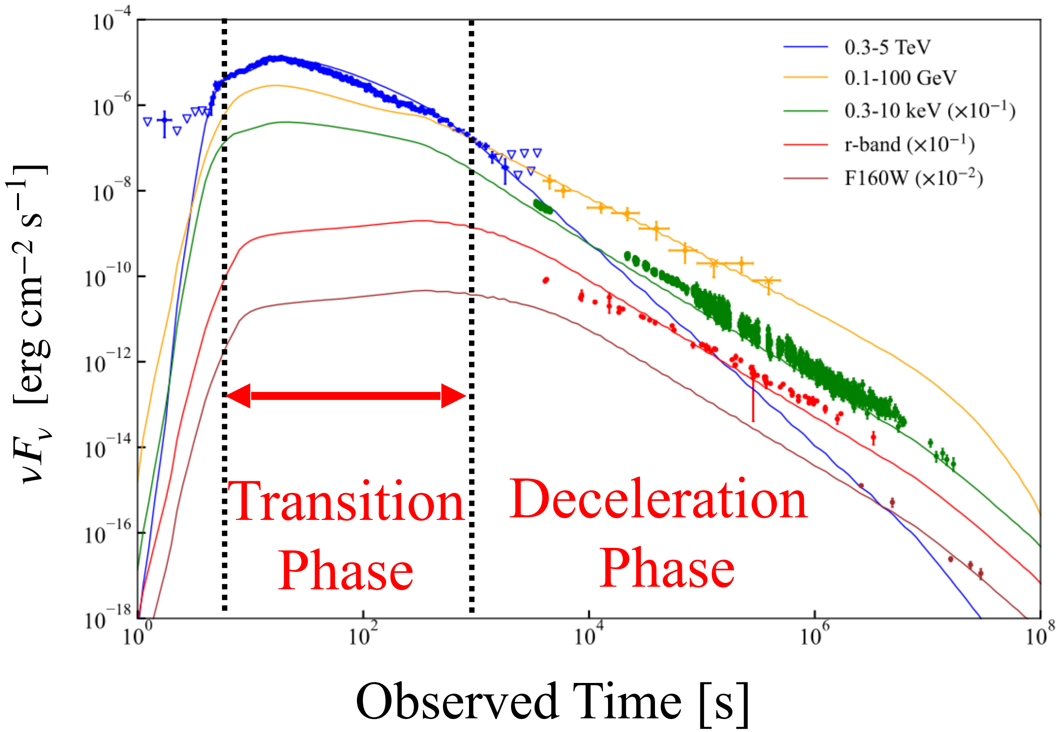
Kusafuka et al. (2025)

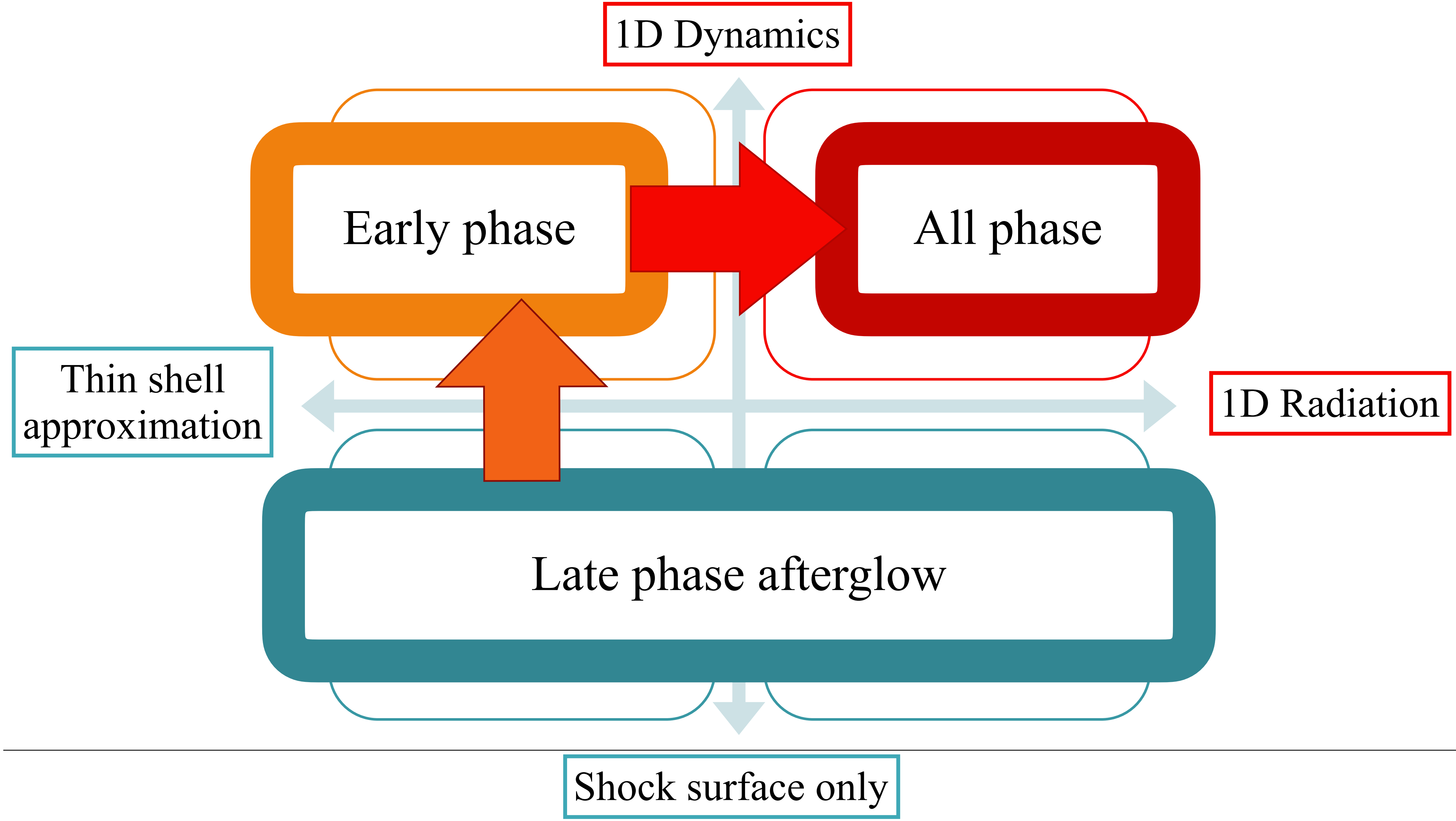
Magglow treat 1D dynamics, but thin-shell radiation

Name	MHD	RS	SSC	pp/pγ	Language
afterglowpy					Python/C
AMES		○	○	○	Python/C++
PyBlastAfterglow		○	○		Python/C++
jetsimpy		○	○		Python/C++
VegasAfterglow	△	○	○		Python/C++
Magglow	○	○	○	○	Julia

BOAT GRB 221009A

Kusafuka & Asano (2025b)

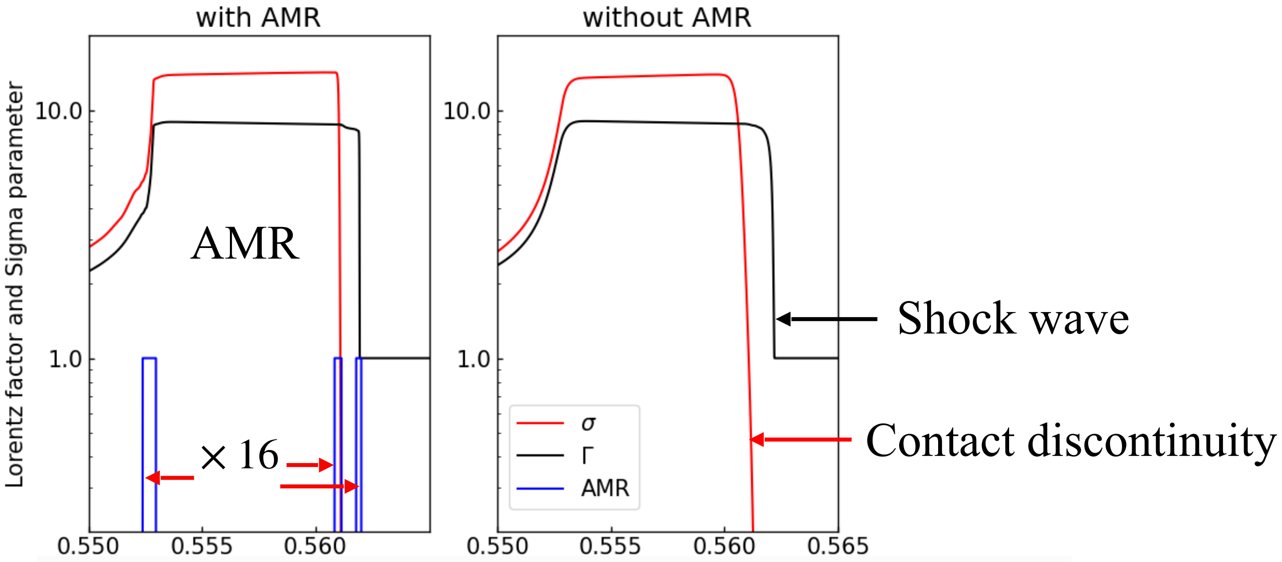


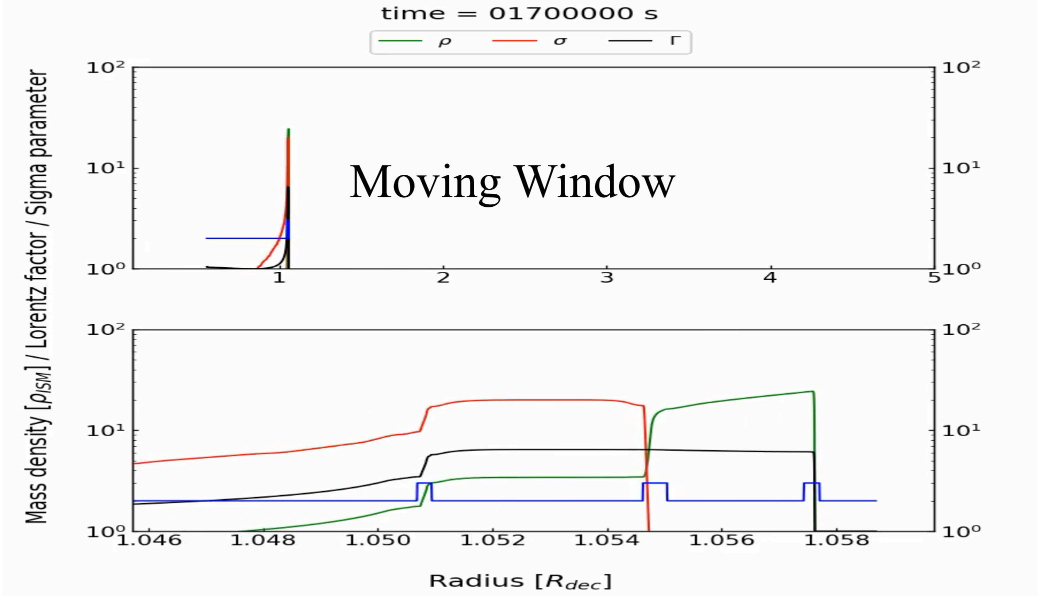

1D Dynamics
Early phase
All phase
Thin shell approximation
1D Radiation
Late phase afterglow
Shock surface only

1D SRMHD Simulation

<u>1D SRMHD code (Kusafuka & Asano (2024))</u>

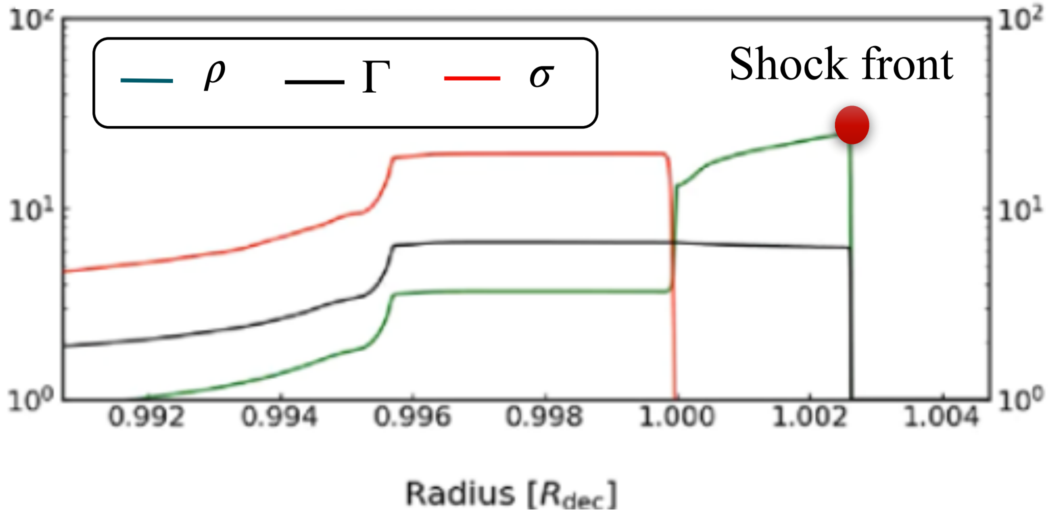
- 7th order **MP7** (Suresh & Huynh 1997)
- 3rd order **SSPRK(3,3)** (Gottlieb & Shu 1999)
- **minmod** flux limiter (Roe 1986)
- **CENTRAL** Riemann solver (Rusanov 1962)
- **MPI** parallel computation (with load balance)
- **AMR** (Berger & Oliger 1984)
- **Moving Window** (Mimica et al. 2004)





1D Lagrange Particle Simulation

Lagrange particles are injected into the shock front

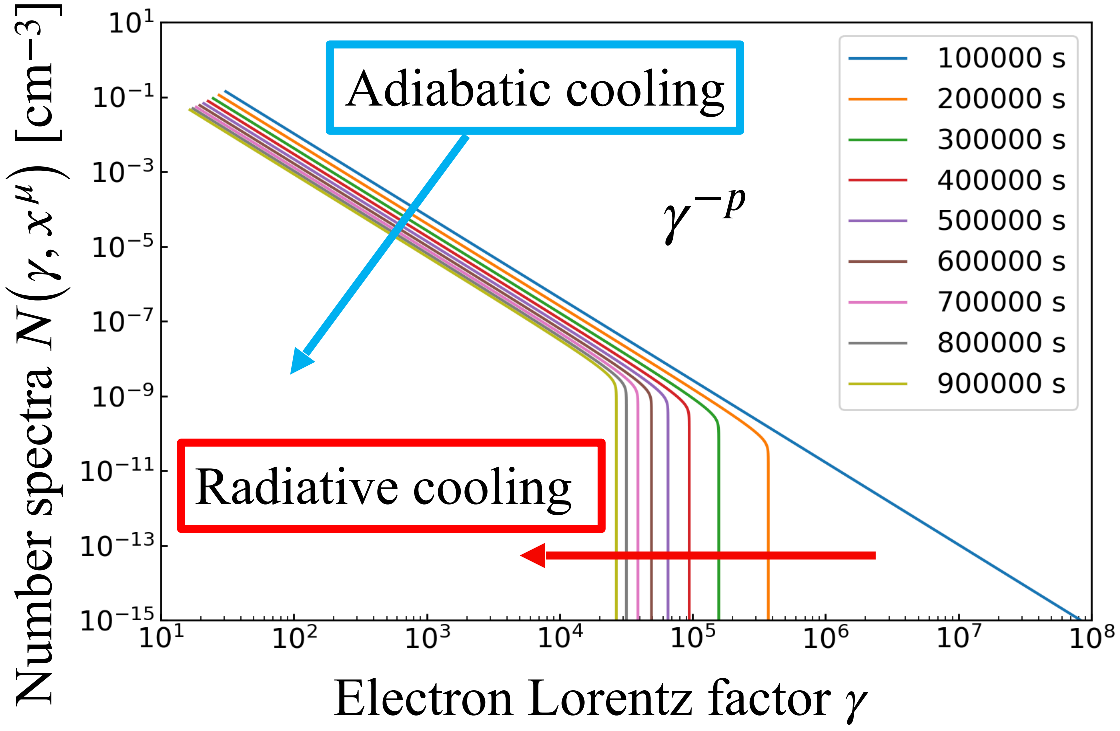


Cosmic ray transport equation

$$\Gamma\frac{d}{dt}\left(\frac{n_p}{n_{MHD}}\right)+\frac{\partial}{\partial\gamma}\left[\Gamma\frac{d\gamma}{dt}\left(\frac{n_p}{n_{MHD}}\right)\right]=0$$

Characteristic curve (Vaidya et al. 2018)

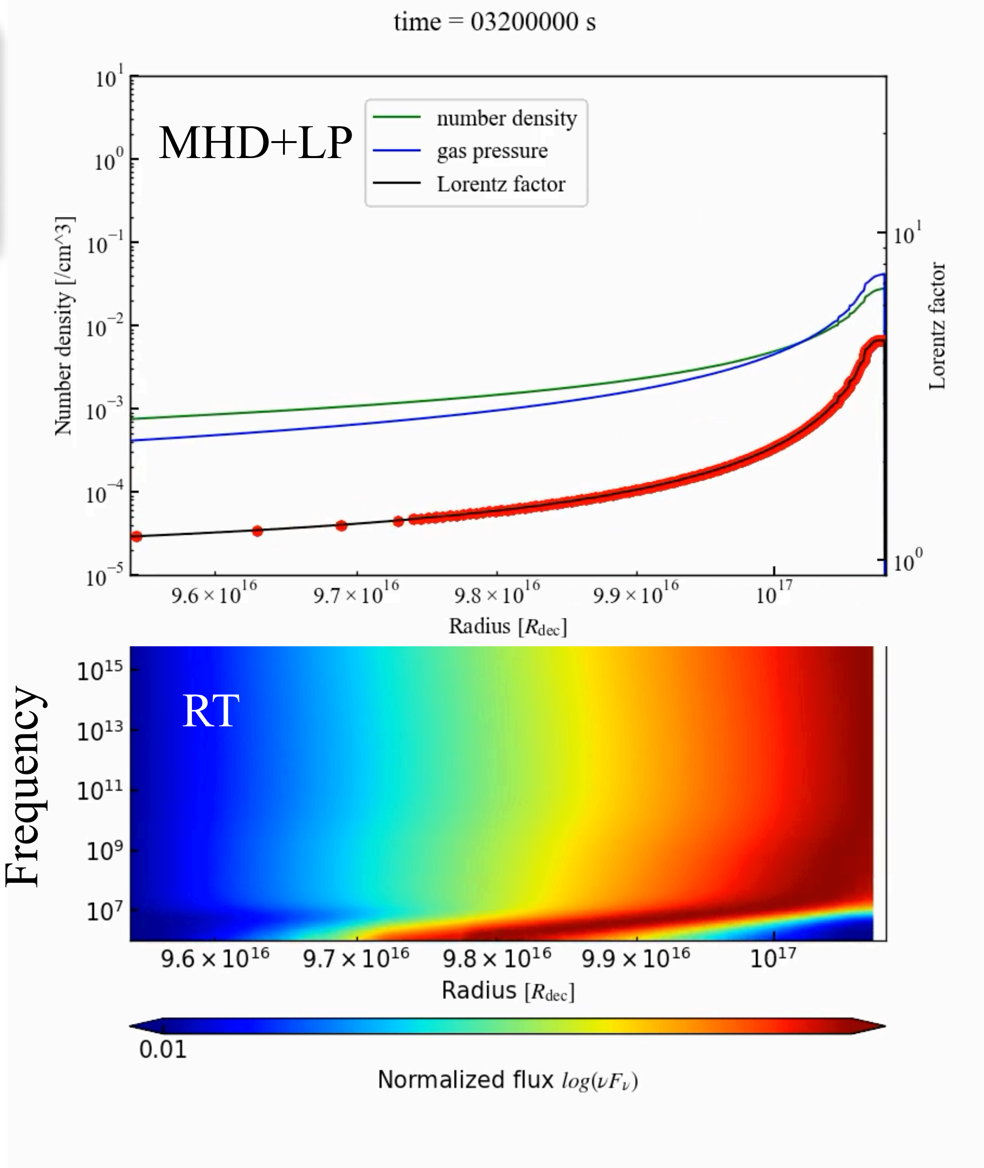
$$\Gamma\frac{d\gamma}{dt}=\dot{E}_{adi}+\dot{E}_{syn}+\dot{E}_{IC}+\dot{E}_{pp}+\dot{E}_{p\gamma}$$



1D Radiative Transfer Simulation

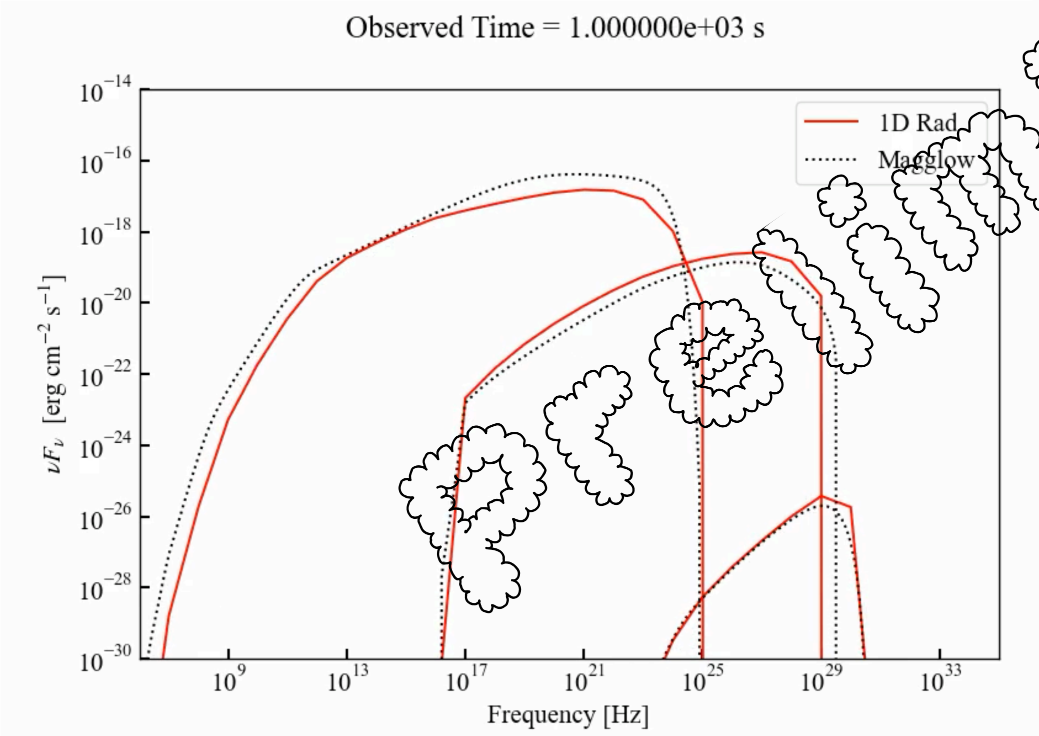
1D RT code (Kusafuka & Asano (in prep))

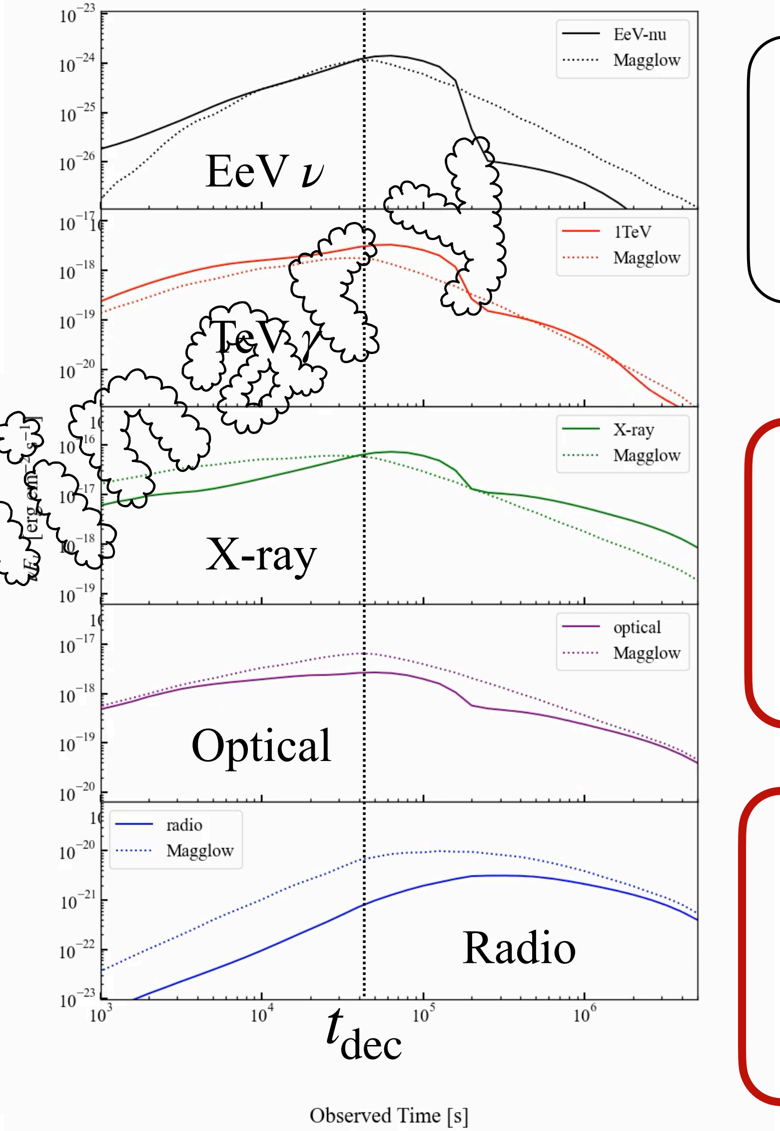
- 7th order **MP7** (Suresh & Huynh 1997)
- 3rd order **SSPRK(3,3)** (Gottlieb & Shu 1999)
- **minmod** flux limiter (Roe 1986)
- **HLL** Riemann solver (Harten et al 1983)
- **MPI** parallel computation (with load balance)
- **Impact parameter** (Hummer & Rybicki 1971)
- **Moving Window** (Mimica et al. 2004)
- **Moving Mesh Refinement** (along a ray)



Spectral Evolution

FORWARD SHOCK





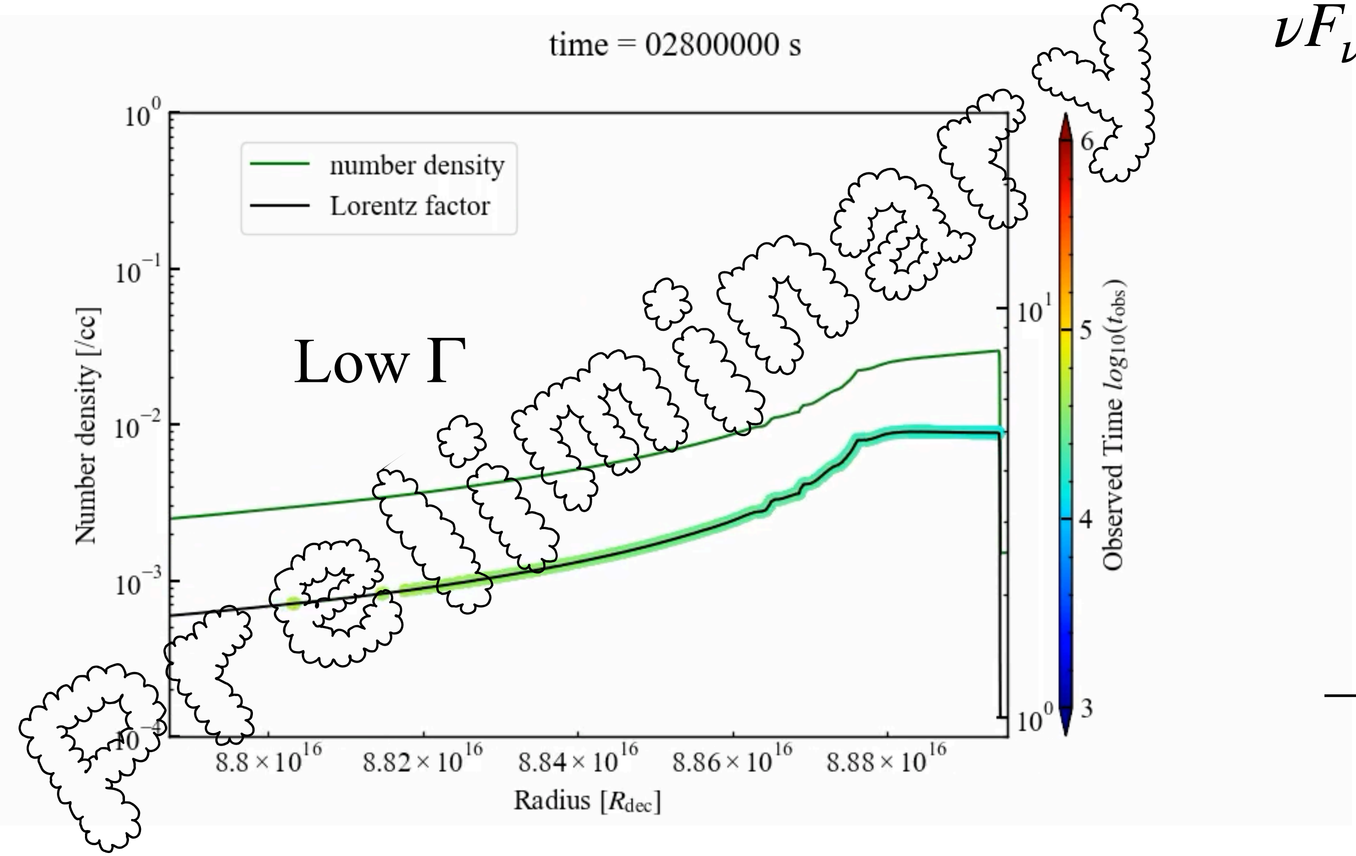
$\Gamma_0 = 10$ $E_0 = 10^{50}$ erg

$\sigma_0 = 10$ $n_{\rm ISM} = 1$ cm^{-3}

Spectral sudden shift
with
Steep & shallow decay

Bright X-ray
with
Late optical flattening

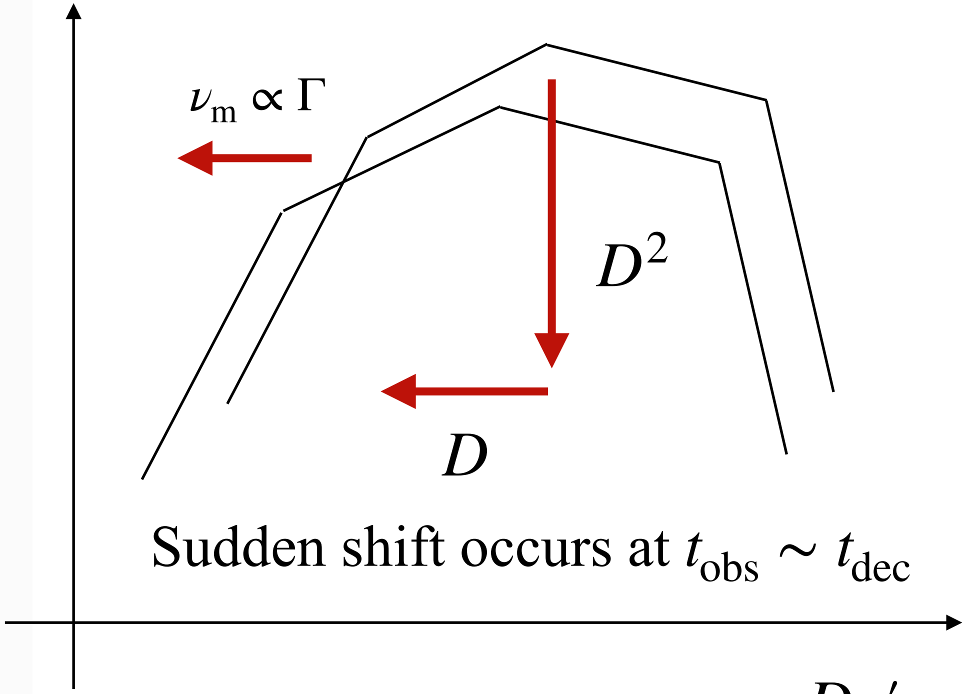
What causes spectral shift?



Decrease Doppler factor in the rarefaction region

$$D = \frac{1}{\Gamma(1-\beta)}$$

$\nu F_\nu \propto D^2$



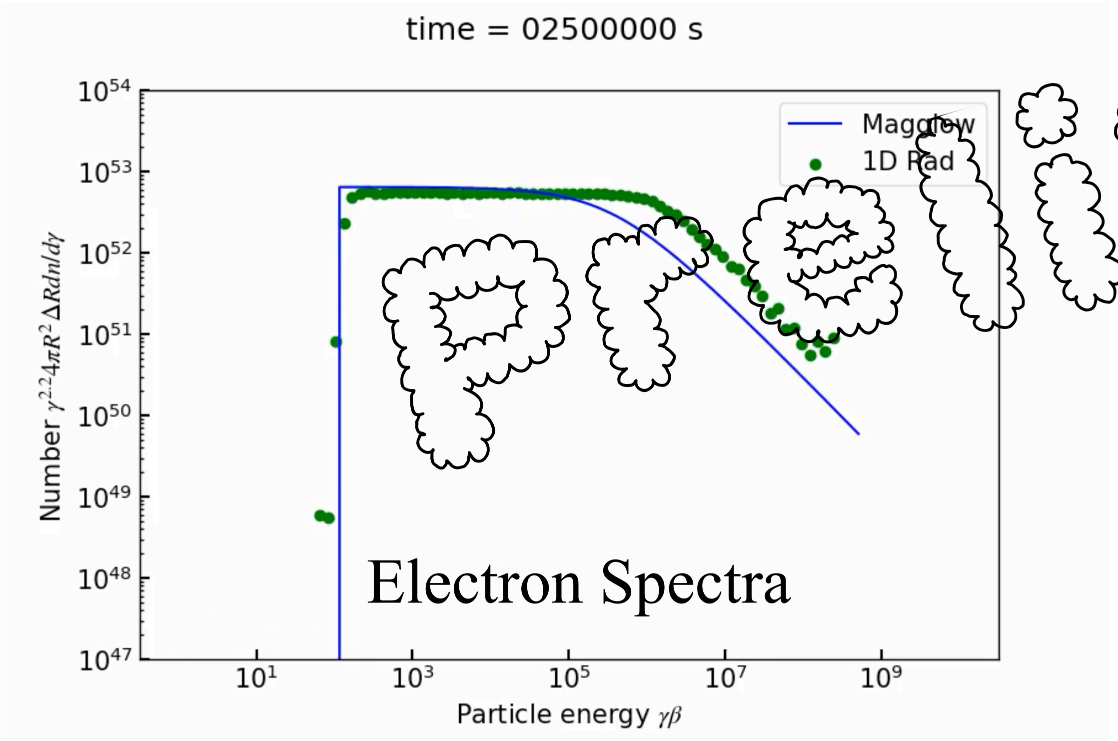
$\nu_{\rm obs} = D\nu'$

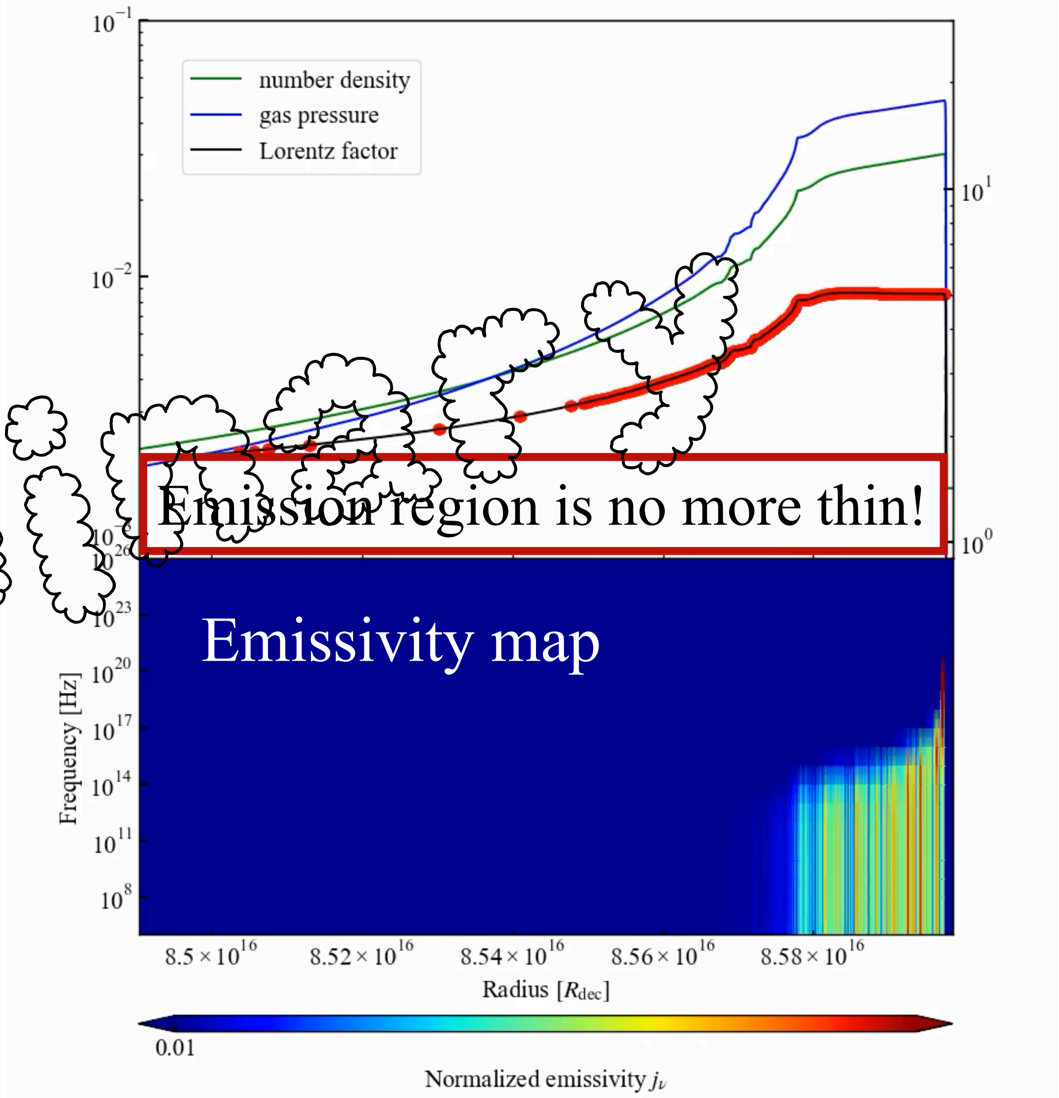
Rarefaction waves might regulate steep & shallow decay

What causes bright X-ray?

Weak coolling

Prelim

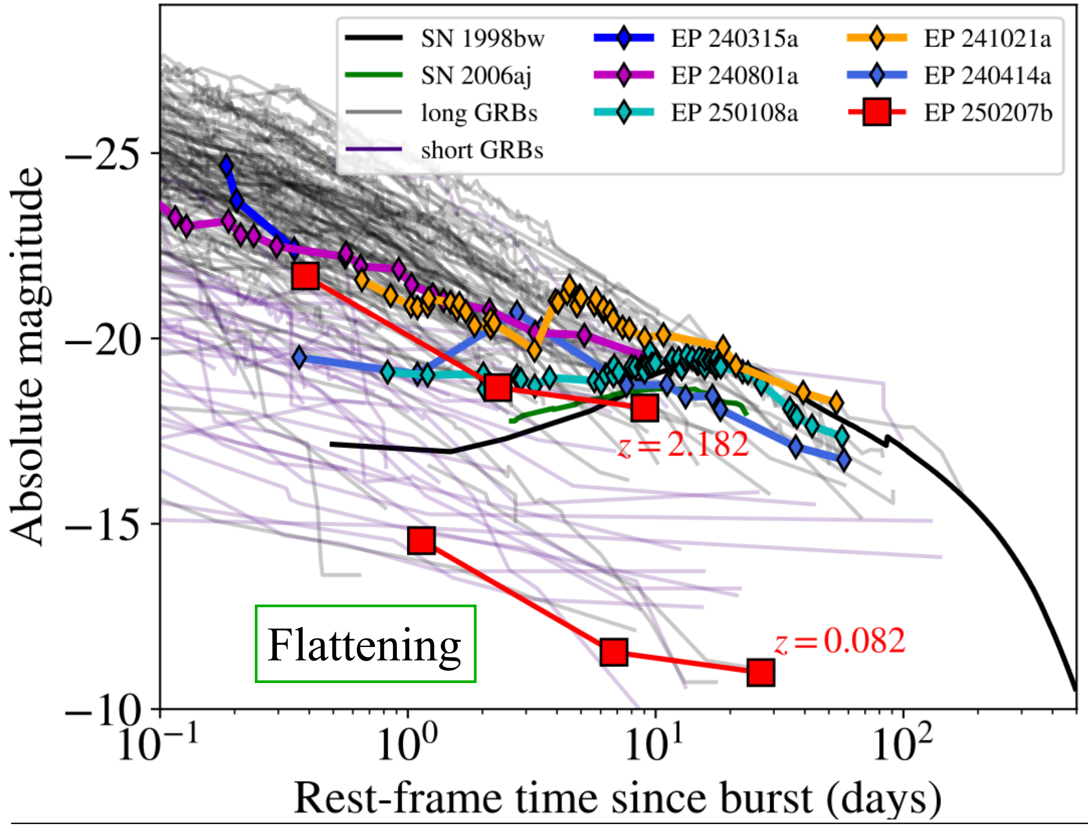




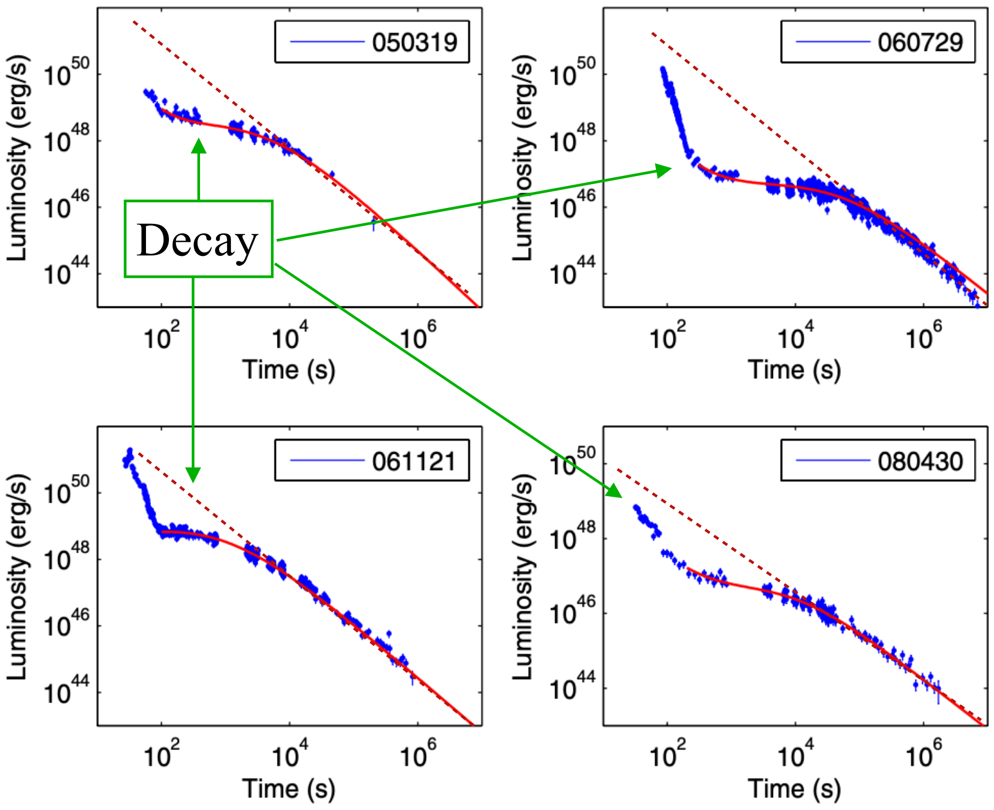
Thin shell underestimates for trans-relativistic shock (e.g. Ferguson &Margalit 2025)

Observational evidences?

Late flattening (Jonker et al. 2025)

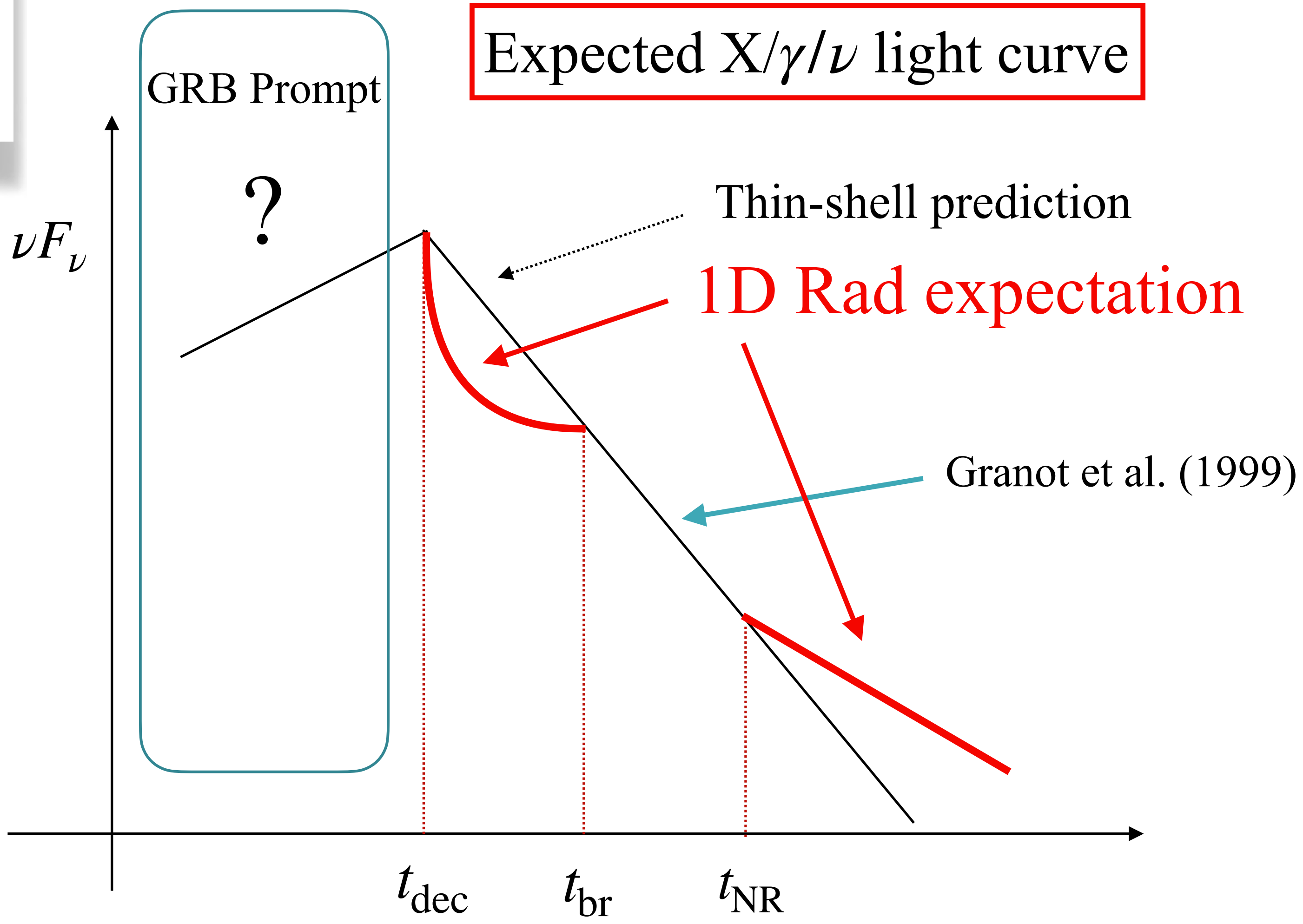


X-ray steep & shallow decay (Dass'Osso et al. 2011)



Summary & Expectation

- At $t \sim t_{\rm dec}$ ($\sim 10^2$ s) : steep decay
- At $t = t_{\rm br}$ ($\sim 10^3$ s ?) : shallow decay
- At $t < t_{\rm NR}$ ($\sim$ a few day) : normal decay
- At $t = t_{\rm NR}$: flattening (also radio/optical)



I hope that simultaneous detection of GeV/TeV γ steep & shallow decay by CTAO!!!